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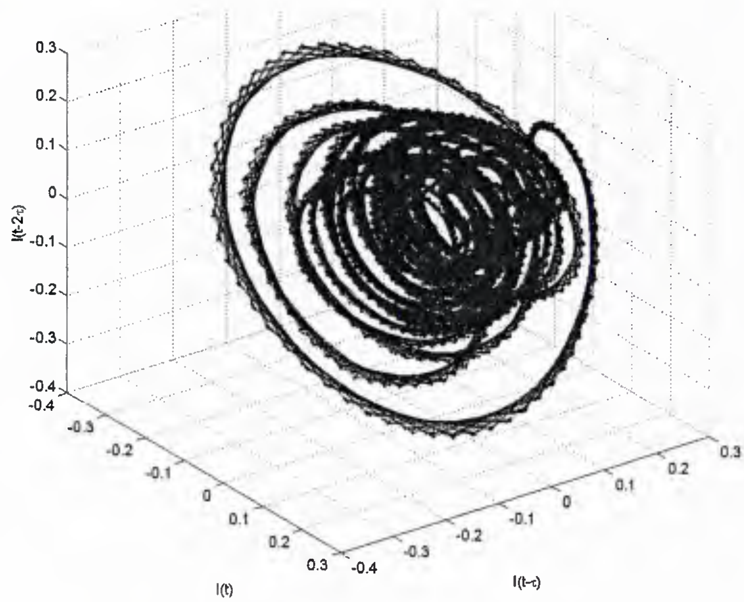
MEMORANDUM

From: Bill Jemison
To: Dr. Daniel Tam, ONR
Date: 4/15/2013

Subject: Progress Report 010–
Chaotic LIDAR for Naval Applications: FY13 Q2 Progress Report (1/7/2013– 3/31/2013).

This document provides a progress report on the project "Chaotic LIDAR for Naval Applications" covering the period of 1/1/2013–3/31/2013.



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FY13 Q2 Progress Report: Chaotic LIDAR for Naval Applications

This document contains a **Progress Summary for FY13 Q2** and a **Short Work Statement for FY13 Q3**.

Progress Summary for FY13 Q2

A high power, wide bandwidth green optical transmitter has been developed which is suitable for experimental underwater LIDAR work. Previous reports have detailed the generation of 50 mW of 532 nm green light with wideband frequency content appropriate for high resolution ranging in water.

This report details improvements to the laser design in efficiency and signal output and also presents our first experimental demonstration of chaotic behavior.

Two preliminary proof-of-concept system experiments are also presented. The first shows rangefinding with centimeter accuracy using a digital receiver for unambiguous ranging at arbitrary distances. In the second experiment, we use the laser signal to probe an unknown channel and determine its frequency response. This technique for finding the instantaneous underwater channel response will be useful for determining best operating conditions for wideband transmitters.

Detailed Description of Work Performed

Chaotic Fiber Laser Upgrade

The chaotic fiber lasers previously reported included a circulator-based ring resonator (FY12 Q1) and a Fabry-Perot reflector cavity (FY13 Q1), both with a novel ultralong cavity for sharp autocorrelation. Both configurations delivered wideband signals at high frequencies, but both suffered from drawbacks: the ring resonator had low power efficiency, while the Fabry-Perot had good power output but its autocorrelation had significant sidelobes at the cavity round trip time. Thus the ring resonator laser was unable to drive the frequency-doubling circuit to produce green light, while the Fabry-Perot did not provide robust unambiguous ranging. These issues led to a re-design of the chaotic fiber laser, which we

Table 1. Comparison of Chaotic Fiber Laser Configurations (Analytical)

Value	Circulator	Reversing Reflector [1]	Feedback Reflector [2]
Minimum cavity losses	7.4 dB	1.1 dB	3.2 dB
Efficiency	48%	84%	80%
Lasing threshold	80 mW	30 mW	50 mW
Ideal T:R	50:50	80:20	80:20
Ideal fiber length	1.25 m	0.5 m	1.0 m
Wavelength discrimination necessary	16 dB	7.5 dB	7 dB
Single-pass gain necessary	22 dB	8.1 dB	13.1 dB
Estimated output power (norm.)	**0.44**	**1.0**	**0.86**

[1] Design from L. Wei, *Fiber Lasers and Resonators*, PhD. Thesis, U. of Waterloo, 2000
[2] From YJ Cheng et al., "Stable single-frequency traveling-wave fiber loop laser with integral saturable-absorber-based tracking narrow-band filter." *Optics Letters* 20.8 (1995): 875-877.

now present as successfully upgraded for high efficiency unambiguous ranging.

The infrared ring resonator laser was inefficient largely because it included a circulator, which has high (>4 dB) loss at 1064 nm. We therefore investigated several ring laser configurations that did not include circulators, and experimented with two: a reversing-reflector model and a feedback-reflector version. Analysis clearly showed that the efficiency in both cases would be much higher than that achieved by the circulator laser (see Table 1), but wavelength control and output signal were issues for investigation. It was found experimentally that the feedback-reflector gave better wavelength stability, and produced the desired output signal, unlike the Fabry-Perot and reversing-reflector configurations (see Figure 1).

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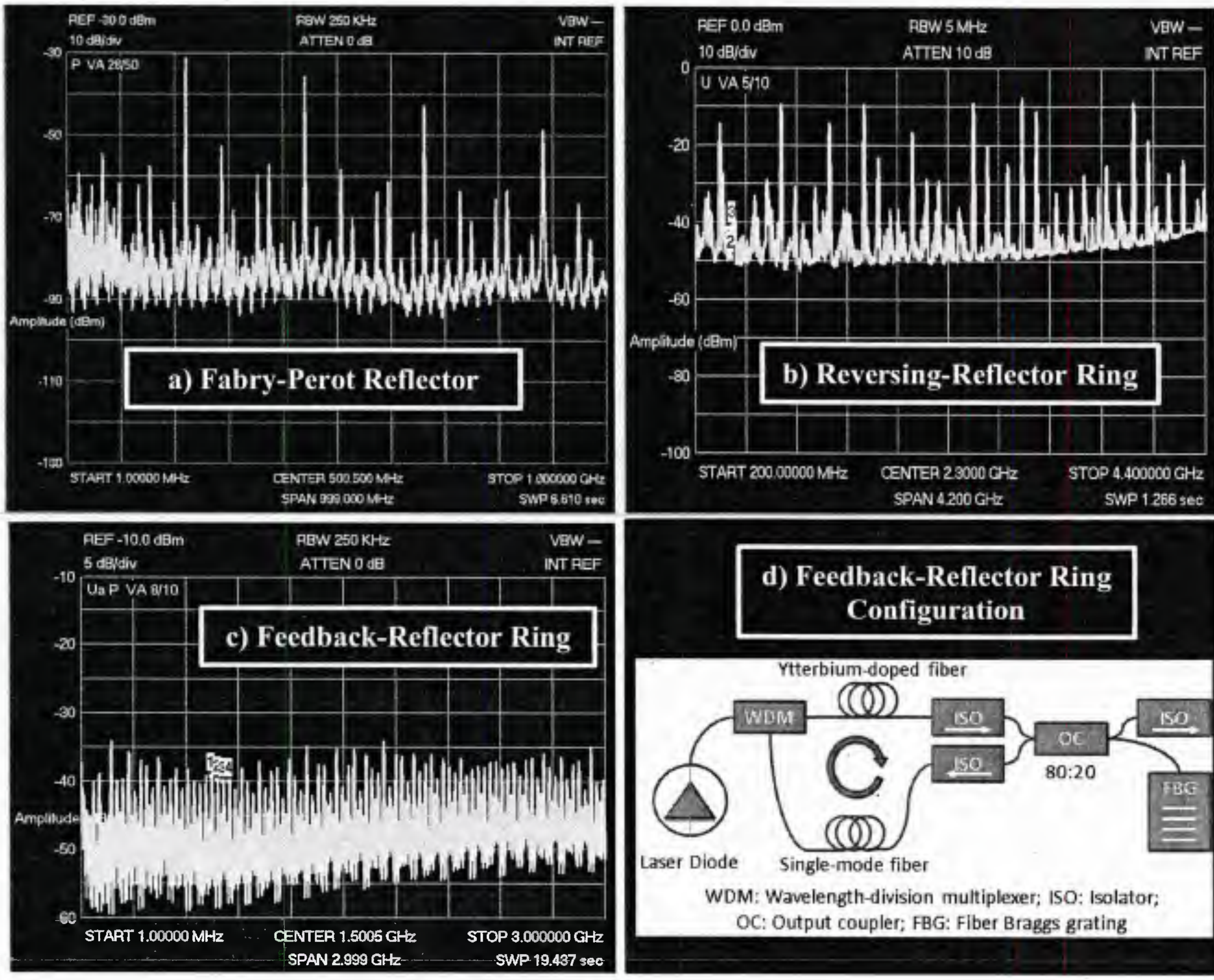

Figure 1. Comparison of three chaotic fiber laser configurations (experimental). The Fabry-Perot and Reversing-Reflector Ring architectures produced non-flat, non-uniform power spectral densities. The Feedback-Reflector Ring generated the flat, uniform spectrum desired for high-resolution ranging.

Because the reversing-reflector output signal had a flat power spectral density (PSD), the time-domain output was noiselike, and the autocorrelation was thus sharp and unambiguous, with none of the sidelobes previously observed using the Fabry-Perot configuration (Figure 2). We observed an autocorrelation peak of <1 ns wide (3 dB) that is limited by our sampling equipment. Thus, we have upgraded the chaotic fiber laser to one better suited for high resolution work underwater, with a sharper autocorrelation and no range ambiguity.

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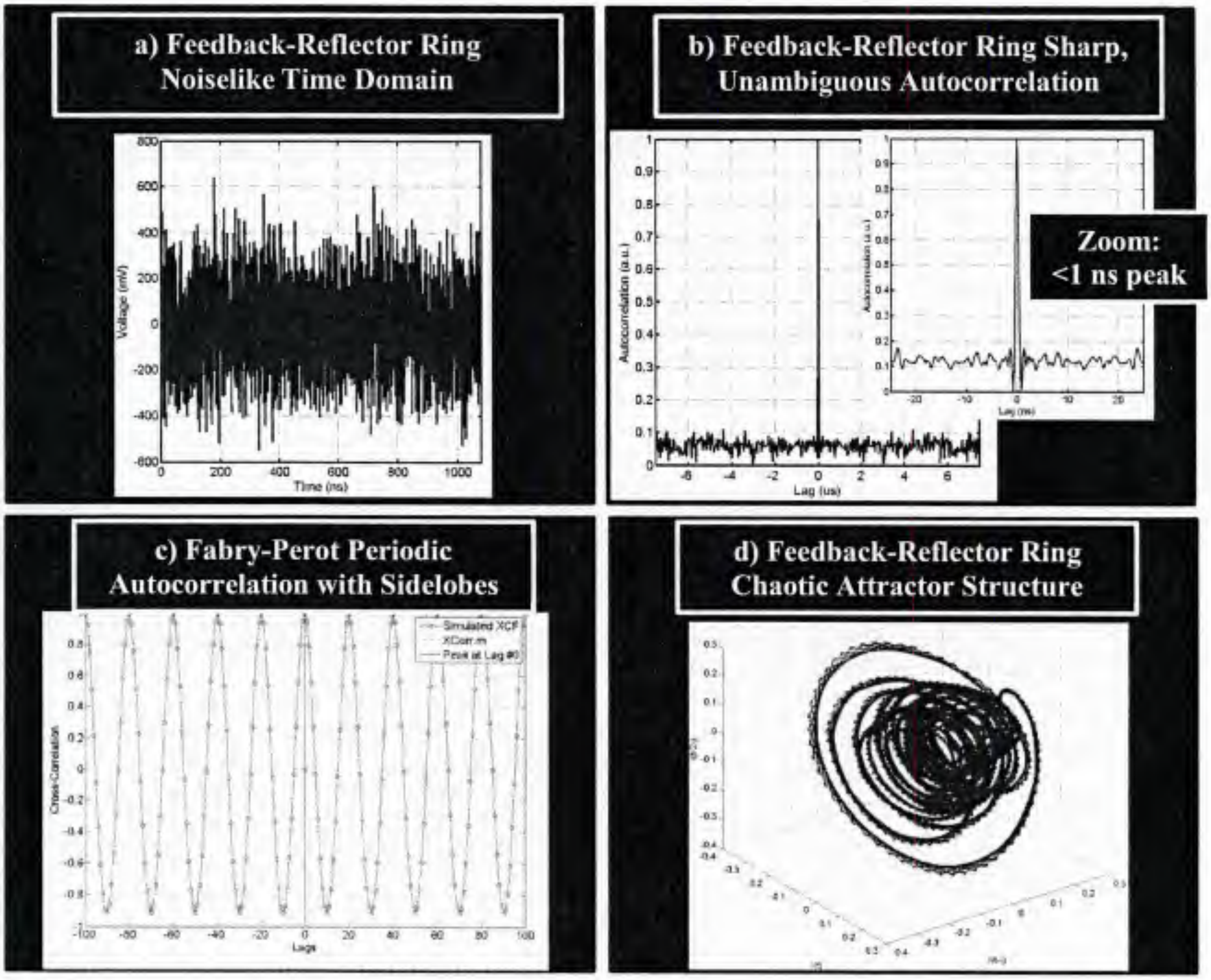

Figure 2. Output signals from Feedback-Reflector Ring. The noise-like time domain signal produces a sharp, unambiguous autocorrelation, unlike the previously implemented Fabry-Perot laser. The signal also exhibits an interesting non-linear attractor behavior, indicative of high-dimensional chaos.

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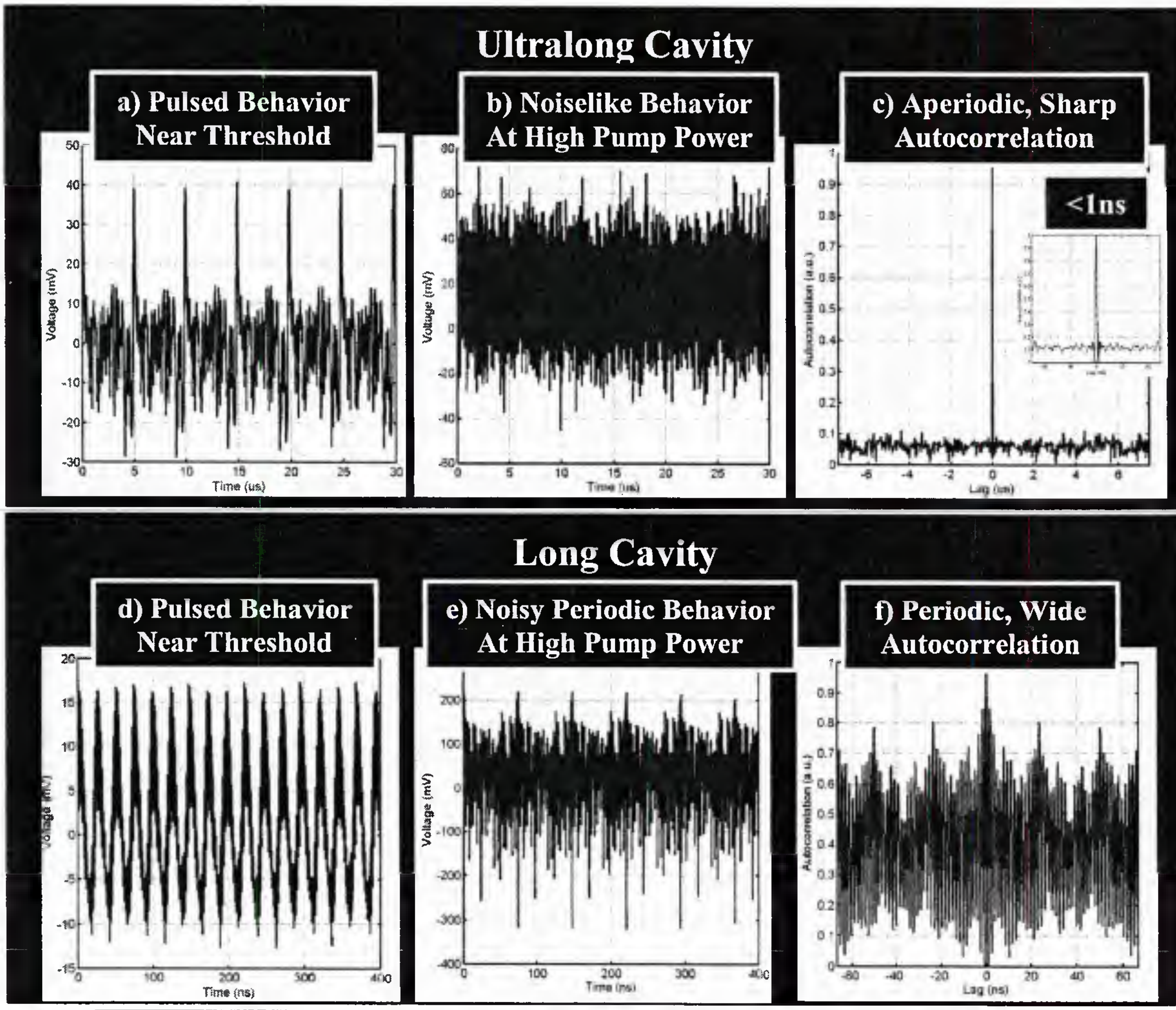

Figure 3. Enhancement of chaos in ultralong cavity fiber lasers. The novel "ultralong cavity" (~1 km) laser becomes chaotic much more quickly, and much more fully, than the traditional "long cavity" (~20 m) version. No periodic behavior is retained in the ultralong cavity approach.

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Nonlinear Analysis

Fiber lasers are optical feedback systems, and are known to exhibit deterministic, nonlinear behavior under certain conditions. As the input pump power is increased from zero, ring lasers have been observed to progress through behavior stages including continuous-wave (CW) with no modulation, periodic self-pulsing modulation (SPM) and high-dimensional chaos. We observe a similar progression with our feedback-reflector ring laser, going from sharp pulses near the lasing threshold, to SPM, and on to chaos. Interestingly, this progression is highly accelerated when we go from a traditional "long cavity" (~20 m) to our novel "ultralong cavity" (~1 km), and the chaotic behavior is much more dramatically noiselike (Figure 3). This is because the ultralong cavity introduces many more modes to compete for gain, and the interactions become chaotic even at low pump powers. Thus as a chaos generator, our ultralong cavity laser has significant threshold and efficiency advantages over previously published work.

Nonlinear analysis has been performed on the output signal (we acknowledge helpful collaoration with Clarkson professor Dr. Erik Bollt, a frequent publisher on chaos and an active ONR researcher). Extracting the embedding delay τ from the average mutual information in the signal, we produced a 3D phase plot, where $x(t)$ is plotted against $x(t-\tau)$ and $x(t-2\tau)$, shown in Figure 2d. In this nonlinear space, the chaotic attractor pattern becomes clear, allowing characterization of the periodicity and confinement of the signal.

Chaos has previously been exploited as a means of securely encrypted communications[1] and enhanced lidar[2] in low-SNR environments, where performance at -15 dB SNR was reported using synchronized chaotic lasers. Leveraging the chaos of our LIDAR transmitter is an area of active investigation.

Rangefinding

A proof-of-concept ranging experiment demonstrates how the new chaotic laser's can be used for high resolution rangefinding. Using a 500 MHz digital receiver, the laser signal was reflected off a target, and the target return was correlated against the transmitted signal. In this proof of concept experiment, the target was a variable length cleaved fiber. The lag of this correlation showed the round trip distance to the fiber cleave. As the relative path distance to the fiber cleave was changed, the lag of the correlation peak likewise changed. As shown in Figure 4, the results show sub-centimeter accuracy relative to the measured length of fiber, with no ambiguity and good resolution associated with the sharp and aperiodic autocorrelation peak.

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[1] Vanwiggeren, Gregory D., and Rajarshi Roy. "Communication with chaotic lasers." *Science* 279.5354 (1998): 1198-1200.

[2] Wu, Wen-Ting, Yi-Huan Liao, and Fan-Yi Lin. "Noise suppressions in synchronized chaos lidars." *Opt. Express* 18.25 (2010): 26155-26162.

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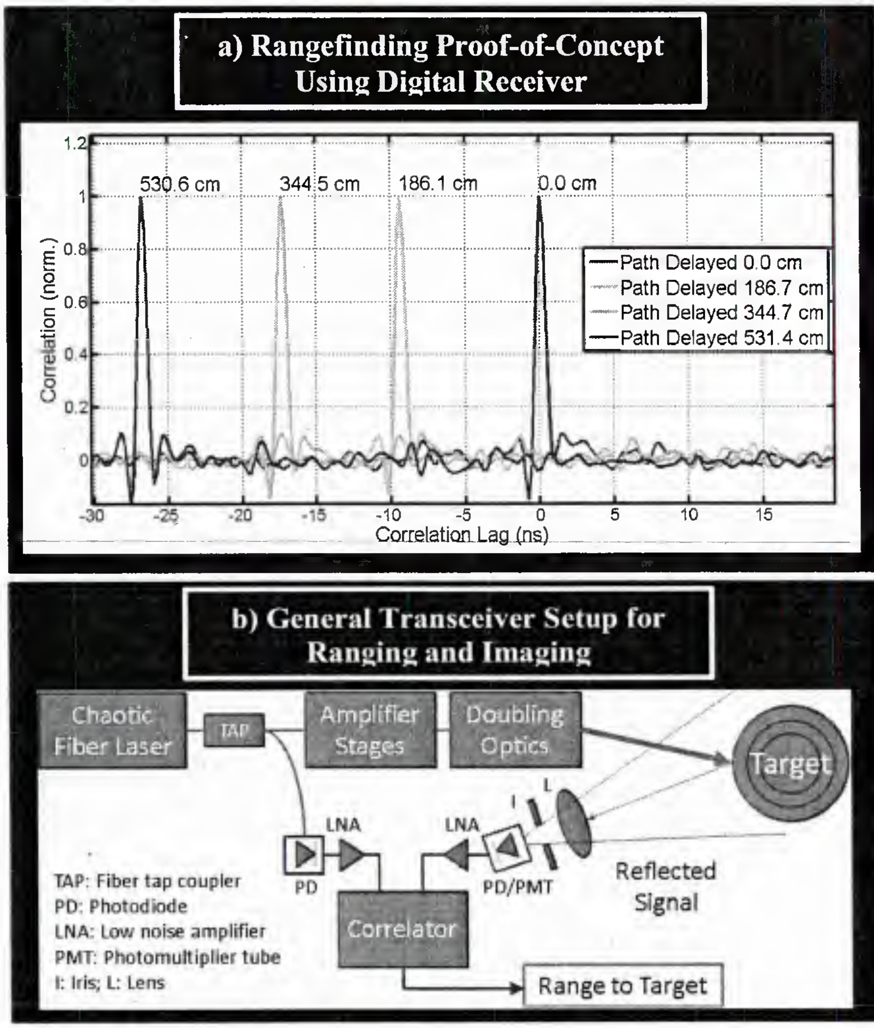

Figure 4. High resolution ranging and imaging using the chaotic LIDAR transmitter. A proof-of-concept experiment shows sub-centimeter ranging accuracy. Either an analog (proximity detection) or digital (rangefinding) correlator can be used. The resolution, i.e. peak width, will depend on the photodetector and correlator bandwidths. The "target" in this proof-of-concept experiment was a reflection off a cleaved fiber of variable length.

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Channel Identification

A second proposed use of this wideband noiselike signal is for underwater channel identification. Here we show a proof-of concept experiment that identifies the channel characteristics by adaptive filtering. Part of the laser output is transmitted through the unknown channel and another part of the laser output is passed through an adaptive filter. The filter taps are adaptive to make the filter output match the unknown channel output. When this condition is met, the adaptive filter characteristic defines the previously unknown channel characteristics.

A proof-of-concept experiment is shown in Figure 5. As shown, the signal is split and sent into both the "unknown channel" to be characterized and into an adaptive filter. The filter coefficients then adjust to minimize the difference (error) between the signal filtered by the unknown channel, and the signal filtered by the adaptive filter. When the error goes to zero, the adaptive filter's response is known to match the unknown channel's. In this experiment the unknown channel characteristic is selected *a priori* to demonstrate the approach. Here, a lowpass FIR filter is was chosen as the "unknown channel", and its response is compared with the adaptive filter's estimation. The close comparison shown in 5b validates the approach, which will be used in upcoming experiments to probe water channels.

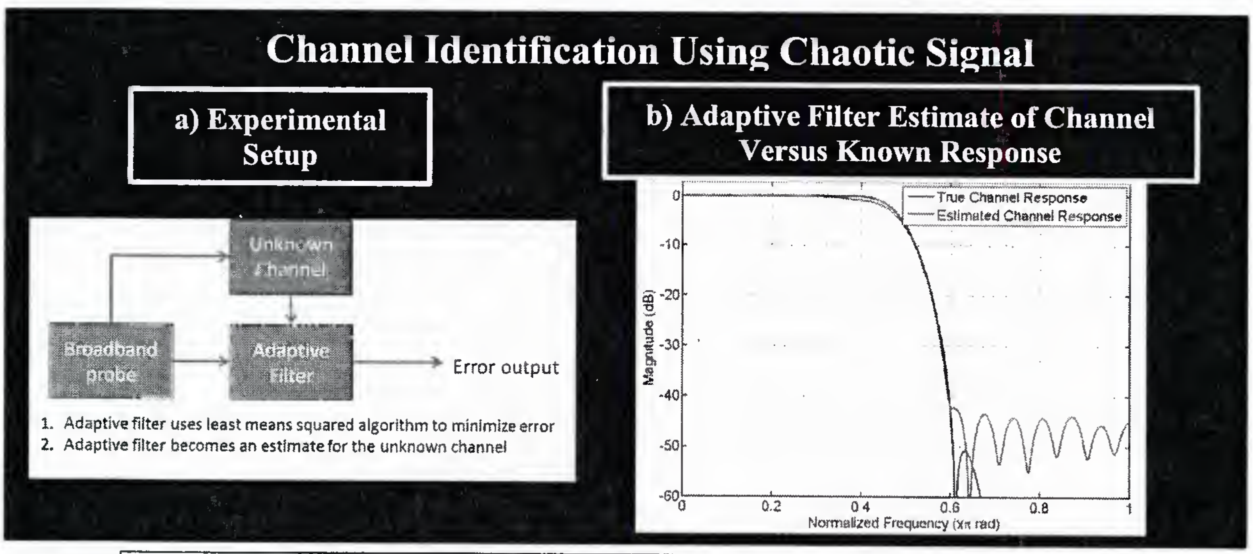

Figure 5. Channel identification using the noiselike chaotic signal. A proof-of-concept experiment shows that an adaptive filter can be used to estimate the frequency response of an unknown channel. This approach can be used to probe an underwater channel to obtain the modulation frequency response, informing operation of wideband transmitters.

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Short Work Statement for FY12 Q3

The chaotic LIDAR transmitter will be used for system experiments showing accurate ranging using both analog (proximity detection) and digital (arbitrary rangefinding) receivers. Instantaneous channel identification will be also performed underwater using the transmitter's wideband, noiselike signal. We will assess the capabilities of the transmitter for rangefinding and channel identification in a variety of scattering-limited turbid water conditions.

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